Energy xxx (2018) xxx-xxx

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com

Evaluation of the performance and degradation of crystalline silicon-based photovoltaic modules in the Saharan environment

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
PV modules
Performance
Degradation rate
Sahara

ABSTRACT

The aim of this paper is to present three years of an evaluation of the performance and degradation rate of three different crystalline silicon-based photovoltaic (PV) modules in the Saharan environment. The PV modules are: mc-Si (multi-crystalline), c_Si (mono-crystalline, back contacted) and HiT (heterojunction with intrinsic thin-layer); they are installed in Saida which is located at the proximity of Algeria's Sahara. Two methods were used to calculate the degradation rate; the effective peak power of the PV modules and the temperature corrected performance ratio. It was found that the HIT technology performs worse than the other technologies with the highest degradation rate, ranging from −1.53%/year to −1.92%/year. The mc_Si PV and c_Si PV module technologies present a lower degradation rate than the HIT technology in the range of −0.74%/year to −0.83%/year and −0.58%/year to −0.79%/year respectively.

1. Introduction

In 2015 the silicon solar cells market share was over 90%, being the main technology used in the manufacturing of PV modules [1]. Moreover, hetero-junction intrinsic thin layer (HiT) silicon PV modules are also increasing their market share due to their high efficiencies over 25% [2].

On the other hand, several countries such as Algeria, Saudi Arabia, Jordan or Chile, all with extreme desert zones, have been identified as emerging markets in PV due to the development of specific photovoltaic energy programs and the high increase of total PV energy capacity in these countries [1]. The performance of crystalline based PV modules in desert environment is strongly influenced by the specific climatic conditions associated to these regions such as high level of solar radiation and extreme temperatures. Moreover, the effect of dust deposition on PV modules in desert environment results in important losses in the generated power [3–6].

Several studies have been recently reported about the performance of PV modules in desert conditions of work. Electrical degradation up to 12% respect to their initial state was observed in crystalline PV modules after a period of 11 years of operation in a region of the Algerian Sahara [7]. Moreover, degradation rates of crystalline PV modules in the Saharan environment ranging from −1.15%/year to −7.87%/year were obtained after long term outdoor exposure [8].

Regarding to the HiT PV modules, it was found that the HIT modules can maintain high values of performance ratio and efficiency in arid climates [9]. However, an average peak power reduction fo 3.9% was found in 28 months of exposure in Indian climate conditions for HiT PV modules [10].

This work presents an analysis of three PV module silicon based technologies under outdoor long term exposure in semi-arid climate conditions at the north of the Sahara desert in Algeria. The period of the study include three years of monitored data, from January 2014 to December 2016. The aim of this work is to carry out a performance analysis of crystalline silicon-based photovoltaic modules in the Saharan environment in order to determine the best technology for desert environment.

The paper is organised as follows: Section 2 shows a description of the PV modules and the monitoring system used in the study. The methodology and techniques used to analyse the behaviour of the PV modules are described in Section 3. Section 4 describes main results obtained and the discussion of the degradation and performance of each PV technology. Finally, in section 5, the most relevant conclusions are summarised.

2. Description of the PV modules and monitoring system

The PV modules were mounted on a fixed support on the ground, faced to south with a tilt angle of 30° at the University of Saida in Algeria. Saida city is located near the border of high plateaux with an altitude of 868 m, latitude: 34° 49′ 60″ north and longitude 0° 9′ east. This city presents a semi-arid climate with influences of Saharan climate especially in the summer.

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https://doi.org/10.1016/j.energy.2018.03.135
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The three PV modules considered in this work correspond to the following silicon based technologies: mc-Si (multi-crystalline), c_Si (mono-crystalline, back contacted) and HiT (heterojunction with intrinsic thin-layer). The main parameters of the PV modules used in this study at standard test conditions (STC): G = 1000 W/m^2 AM1.5G, Tc = 25 °C, are given in Table 1.

The monitoring system includes a CR1000 data logger by Campbell Scientific that recorded the electrical and meteorological parameters with a sampling time of 10 min.

The electrical parameters of the PV modules were obtained by measuring their I-V curves by a system based on capacitor load. On the other hand, climate parameters where measured by means of a HukseFlux SR20 pyranometer wit tilt response <± 0.2% (0–90° at 1000 W/m^2) for the irradiance (*G*), a Vaisala HMP155 probe with temperature and relative humidity accuracy of ± 0.20 °C and ± 1.7% respectively, and a Young 05106 sensor with an accuracy of ± 0.3 m/s and ± 3° of wind direction. Finally, the modules temperature, T_m, was measured by using T type thermocouple cables attached to the back surface of the modules.

Table 2 shows the annual daily average (Mean) and the standard deviation values (STD) of meteorological parameters recorded during the monitoring campaign.

Fig. 1 shows the evolution of the PV module temperature, monthly average values for G > 700 W/m^2. As it can be seen in Fig. 1, the mc-Si PV module presents the higher module temperature along the whole monitoring campaign, while the c-Si PV module is the module with lower temperature values.

3. Methodology

The monitored data values obtained from January 2014 to December 2016 were analyzed by means of a filtering process. The methodology used in the evaluation of main parameters included in this study is described in this section.

Table 1
Main parameters of PV modules analysed.

Technology	PV module		
	mc-Si	HiT	c-Si
Peak power (W)	165	233	208.5
Isc (A)	8.53	5.84	8.94
Voc (V)	26	51.6	30.6
Temperature coefficient- power δ (%/°C)	−0.47	−0.30	−0.38
Temperature coefficient- Voltage β (%/°C)	−0.33	−0.24	−0.19
Temperature coefficient- current α (%/°C)	0.036	0.030	0.059
Efficiency: η(%)	14.27	18.60	15.40

Table 2
Annual daily average and standard deviation values of the meteorological parameters along the monitoring campaign in sunny hours.

Year	Irradiation (kWh/m^2)		Ambient temp. (°C)		Rel. Humidity (%)		Wind speed (m/s)	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
2014	5.37	1.54	20.54	3.21	44.99	13.31	1.27	0.59
2015	5.53	1.40	20.68	3.20	45.50	12.43	0.95	0.51
2016	5.39	1.60	20.97	3.62	44.39	12.80	1.17	0.46

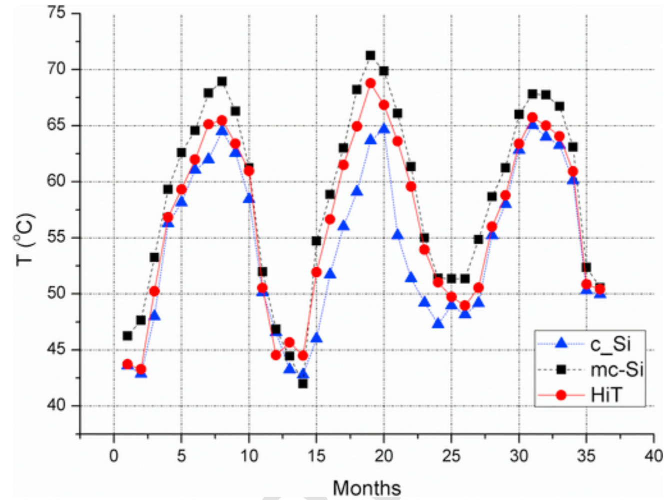

Fig. 1. Module temperature profiles.

3.1. Effective peak power and degradation rate

The degradation rate of the PV modules, R_D, is calculated by analyzing the evolution of the effective peak power P^*_M, of the PV modules along the monitoring campaign.

The P^*_M was evaluated by using the following equation [10–14]:

$$P^*_M = \frac{G^* P_{DC}}{G} Tf \tag{1}$$

where P_{DC} is the DC output power of the PV module, G and G^* are the actual irradiance, and irradiance at STC respectively and Tf is the thermal factor given by the following equation:

$$Tf = \frac{1}{\left[1 + \delta\left(T_m - T^*_m\right)\right]} \tag{2}$$

where δ is the power temperature coefficient of the PV modules given in Table 1 and T_m* is the module temperature at STC.

The values of all parameters corresponding to low irradiance values were not included in the analysis. Only measurements taken at G > 700 W/m^2 were used. Above this irradiance threshold the shape of varying solar spectra closely resembles that of the spectral AM1.5G reference spectrum [11].

The PV modules degradation rate, R_D (%/year), is evaluated by means of a linear least square fitting method of P^*_M by using Eq. (3) [14–16].

$$R_D = 100\frac{12b}{a} \tag{3}$$

where b (W/month) is the slope of the trend line obtained for P^*_M and a(W) is the y-intercept [10,14–16]:

$$y = a + bx \tag{4}$$

3.2. Fill factor

The fill factor of a PV module, FF, is ratio of maximum obtainable power to the product of the open-circuit voltage and short-circuit current given by the following equation:

$$FF = \frac{Vm\ \ Im}{Voc\ \ Isc} \tag{5}$$

where V_m and I_m are the coordinates of the maximum power point (MPP) and V_{oc} and I_{sc} are the PV module open circuit voltage and short circuit current respectively.

3.3. Performance ratio and temperature losses

The degradation analysis can also be performed using the standard performance parameters. For this purpose, the temperature corrected performance ratio is used to estimate the degradation rate for each PV module technology. Subsequently, all the parameters calculated are based on data recorded during sun hours.

The performance ratio, PR, of the PV modules was evaluated by using the following equation [16,17]:

$$PR\,(\%) = \frac{Y}{Y_r}.100 \tag{6}$$

where Y is the array yield that indicates the amount of time during which the array would be required to operate at the array rated output power to provide the monitored DC energy output, E, and Y_r is the reference yield given by the following equations:

$$Y = \frac{E}{P_M^{STC}} \tag{7}$$

where P_M^{STC} is the measured maximum power at STC.

$$Y_r = \frac{\tau \sum G}{G*} \tag{8}$$

where τ is the recording interval.

The temperature is a crucial parameter that affects the performance of PV modules. In order to calculate the temperature corrected performance ratio, PR_{corr}, firstly the temperature corrected DC energy output, E_{corr}, must be performed using the temperature effects with the following equation [18,19]:

$$E_{corr} = \frac{E}{1 + \delta\left(T_m - 25\right)} \tag{9}$$

Thus, the temperature corrected array yield, Y_{corr}, was calculated as follows:

$$Y_{corr} = \frac{E_{corr}}{P_M^{STC}} \tag{10}$$

Therefore, the temperature corrected performance ratio, PR_{corr}, can be calculated by using the following expression:

$$PR_{corr}\,(\%) = \frac{Y_{corr}}{Y_r}.100 \tag{11}$$

The temperature losses decrease the efficiency of the PV array. The temperature losses can be calculated as follows [20]:

$$L_T\,(\%) = 100.\left(E_{corr}/P_M^{STC} - Y\right)/Y_r \tag{12}$$

4. Results and discussion

4.1. Evolution of the effective peak power of the PV modules

Fig. 2 shows the evolution of $P*_M$ obtained for the three PV module technologies. The values correspond to monthly average values calculated after the filtering process described in Section 3.

As can be seen in the figure, the most important reduction of $P*_M$ was obtained for the HiT PV module, with a total power reduction of 6% at the end of the monitoring period. The reduction of power observed in the c_Si PV module is 4.2% while the mc_Si PV module shows the lower power reduction trend with a small increase the last months.

The R_D was calculated by applying Eqs. (3) and (4) to the trend lines of $P*_M$ shown in Fig. 2 for the three PV modules. The values of the R_D obtained are given in Table 3. As it can be seen in the table, the HiT PV module shows the highest R_D. The value of R_D=−1.53%/year obtained for the HiT PV module is a little bit higher than the −0.98%/year reported for HiT PV modules evaluated over five years at the University of Cyprus [21]. However, this value is closer to the values reported for HiT PV modules also analyzed in Cyprus that obtained R_D=−1.28±0.18 for three-year and R_D=−1.64±0.12 after four-year analysis [22].

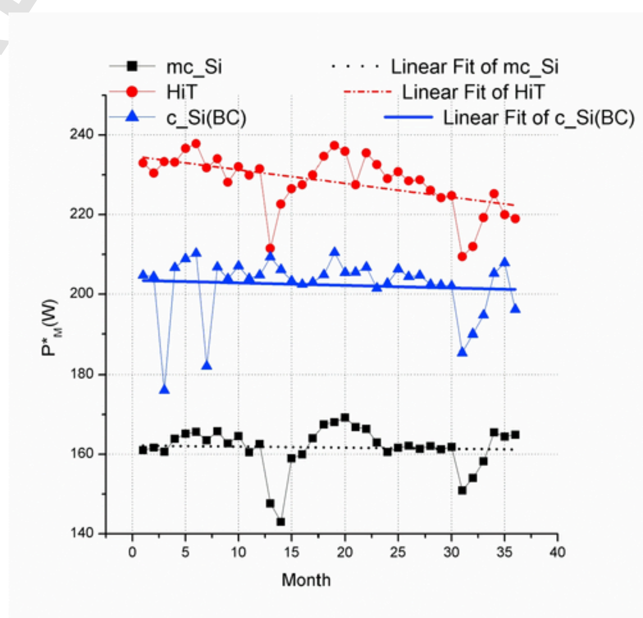

Fig. 2. Evolution of $P*_M$.

Table 3
Degradation Rates of the PV modules.

	PV module		
	c_Si	mc_Si	HiT
Slope (b in Eq. (4))	−0.098	−0.101	−0.301
Intercept (a in Eq. (4))	203.5	162.2	234.7
R_D (%/year)	−0.58±0.01	−0.74±0.008	−1.53±0.03

Regarding the mc_Si PV module, the value of R_D=−0.74%/year obtained in this study is a little bit higher the median value of R_D=−0.64%/year reported in 2011 by Jordan and Kurtz [23] and also higher than the R_D=−0.51%/year observed by Sharma and Chandel [24]. Other works reported average values of R_D=−0.62%/year [21] and maximum values of R_D=−1.27%/year [22].

With respect to the c_Si PV module, R_D=−0.58%/year, this value is in accordance with median values reported in the literature [21,23]. Values up to -1.22%/year were reported for c_Si PV modules after 28 years of exposure in the Saharan environment in Algeria [25].

4.2Analysis of the output voltage and current

The evolution of the output voltage of the PV modules, monthly average values of the voltage corresponding to the MPP, and temperature is shown in Fig. 3. As it can be seen in the figure, the output voltage of the PV modules follows seasonal variations due mainly to the temperature profile. The maximum values of the output voltage correspond to the minimum values of temperature recorded, whereas the minimum values of temperature result in maximum values observed for the output voltages (see Fig. 4).

The effect of temperature on the output voltage of the c_Si PV module is lower than in the other PV module technologies because it presents the lowest voltage temperature coefficient, as it can be seen in Table 1. Despite the mc_Si PV module has the highest voltage temperature coefficient, it seems to show lower voltage variations due to temperature than the HiT PV module. However, this fact can be explained by taking into account that the HiT PV module has an open circuit voltage at STC of 51.6 V, whereas the mc_Si open circuit voltage is 26 V, as it was shown in Table 1.

Concerning the evolution of the output current of the PV modules at the MPP, the monitored profiles are given in Fig. 5 along with the

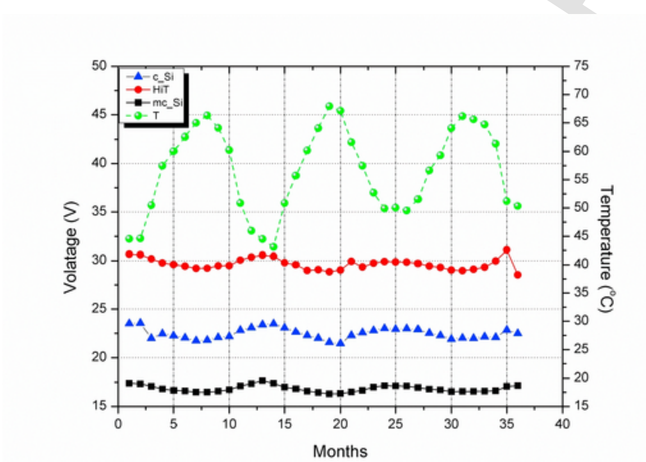

Fig. 3. Evolution of the output voltage of the PV modules.

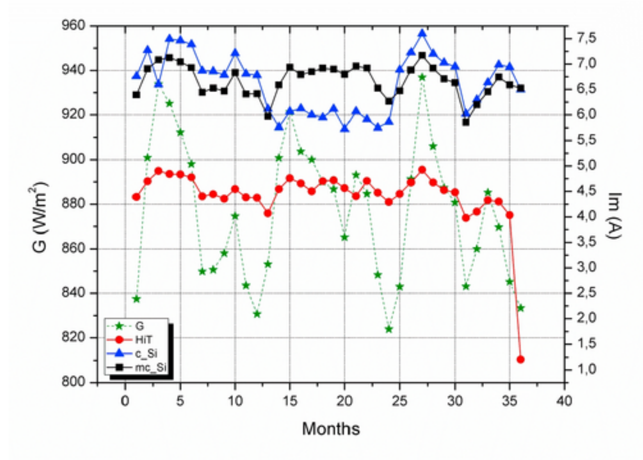

Fig. 4. Evolution of the output current of the PV modules and Irradiance profile.

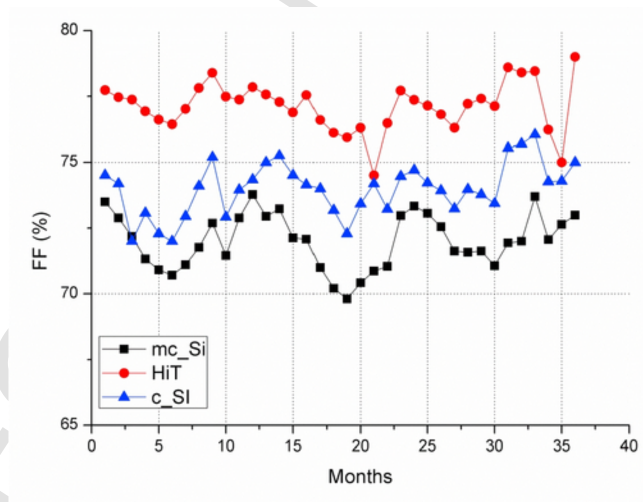

Fig. 5. Fill Factor evolution for all PV modules.

monitored Irradiance profile, monthly average values for measurements taken at G>700 W/m^2.

All PV modules show seasonal variations mainly due to the evolution of the irradiance profile but also affected by the temperature variations. The c_Si and mc_Si PV modules have similar values of shot circuit current at STC. However, the variations observed on Im are more important in the c_Si PV module because it presents the highest value of temperature coefficient for the current, almost the double than the other two PV modules, as it was shown in Table 1.

4.3. Fill factor

Fig. 5 shows the evolution of the monthly average values of the FF obtained for the PV modules along the monitoring campaign.

The FF of the HiT PV module is higher than the FF of the c_Si and mc_Si PV modules along the whole monitoring campaign. All technologies show seasonal oscillations that are more relevant in the case of the mc_Si PV module and less important in the case of the HiT module. The c_Si and mc_Si modules perform better in winter time. Despite this fact, the FF values seem to be quite stable and present higher values at the latest months of the monitoring period.

4.4. Performance ratio

The evolution of the monthly average values of the *PR* evaluated by using Eq. (6) is shown in Fig. 6 for the three PV module technologies. As it can be seen in the figure, the degradation of the *PR* is observed in the three PV module technologies. The mc_Si PV module shows the lowest values of *PR*, whereas the values obtained for the HiT and c_Si PV modules are quite similar, although the *PR* values of the HiT PV module are higher.

The temperature corrected performance ratio, PR_{corr}, was evaluated as it was described in Section 3.3. The evolution of the monthly average values of PR_{corr} obtained for the PV technologies analysed is given in Fig. 7.

The annual R_D were obtained by applying a linear least square fit to the extracted trend of the PR_{corr} curves and evaluated by using Eqs. (3) and (4). The values obtained for the slope, *b*, and intercept, *a*, for each PV module are given in Table 4. As it can be seen in the table, the values obtained for the R_D are slightly higher than the R_D calculated in section 4.1 based in the evolution of P^*_M for all PV module technologies. However, the results are consistent with those presented in Table 3. The PV module that presents the highest value of R_D is the HiT PV module, followed by the mc_Si and the lowest R_D was obtained for the c_Si PV module.

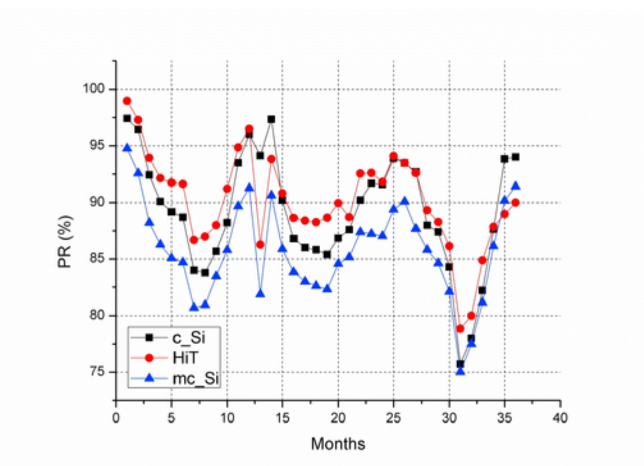

Fig. 6. Monthly average values of *PR*.

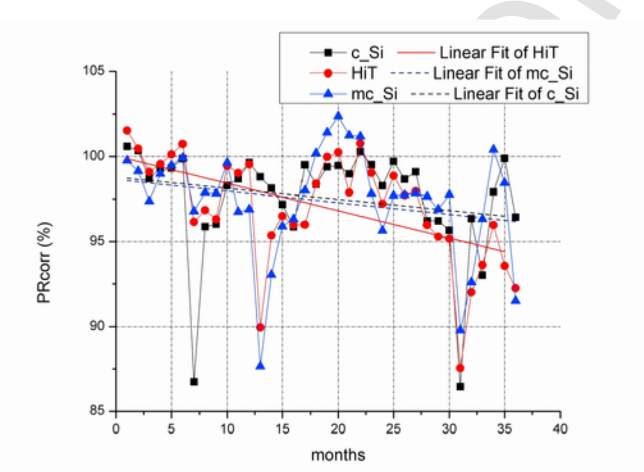

Fig. 7. Monthly average values of *PRcorr*.

Table 4
Degradation Rates of the PV modules obtained from *PRcorr*.

	PV module		
	c_Si	mc_Si	HiT
Slope (b in Eq. (4))	−0.065	−0.068	−0.160
Intercept (a in Eq. (4))	98.73	98.65	100.03
R_D (%/year)	−0.79 ± 0.008%	−0.83 ± 0.01%	−1.92 ± 0.02%

The R_D=−0.83%/year obtained in this study for the mc_Si PV module is in the range of values reported in the literature, R_D=−0.62%/year [21] and R_D=−1.27%/year [22].

Concerning the c_Si PV module, a R_D=−0.79%/year was obtained. This value is lower than the R_D=−1.22%/year reported for c_Si PV modules after 28 years of exposure in the Saharan environment in Algeria [25]. Moreover, the R_D obtained for the c_Si PV module is in the range of values obtained for this PV module technology, from −0.77%/year to −1.37%/year, observed over a five-year period of operation in Cyprus [21] and −0.25% to −1.3%/year [26] reported in Mediterranean climate. This fact seems to indicate that desert climate conditions do not induce to a strong degradation of c_Si PV modules.

Contrarily, the R_D values obtained for the HiT PV module in both analysis, studies of P^*_M and PR_{corr}, are higher than values obtained for this technology in Crypus after a period of study of four years [22]. The R_D=−1.92%/year is very similar to the R_D observed in micromorph TFPV modules after three year operation in Spain [14]. The degradation of HiT PV modules in desert climate conditions is more important than the one observed for the rest of technologies analyzed.

Temperature losses can be an important factor of power losses in PV systems [27–29]. The temperature losses were calculated by using Eq. (12). The results obtained are depicted in Fig. 8 for all PV module technologies under study.

The mc_Si PV module presents the most important temperature losses, up to 19%. The temperature losses of this PV module are higher than the observed in the other two PV modules along the whole monitoring period, followed by the temperature losses observed in the c_Si PV module, being the HiT PV module the one having lower values of losses associated to temperature effects. These re-

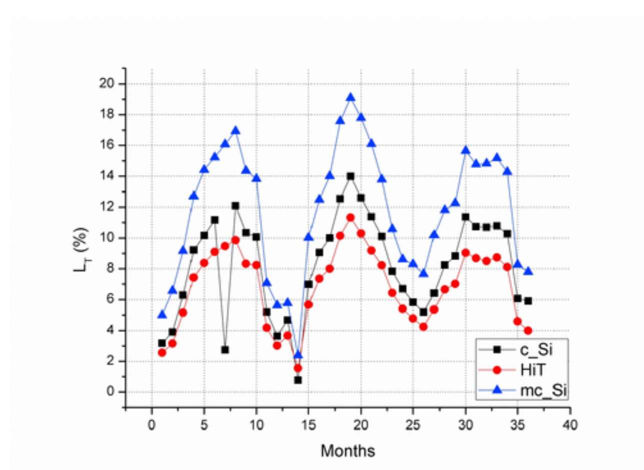

Fig. 8. Temperature losses, L_T, profile.

sults can be explained by considering the temperature coefficients indicated in Table 1 for the three PV module technologies. Moreover, it can be seen that the highest values of R_D observed for the HiT PV module are not due to temperature effects.

5. Conclusion

In this paper, an evaluation of the performance and degradation analysis of three different PV module technologies has been presented. The three PV modules analyzed are silicon based technologies: mc-Si (multi-crystalline), c_Si (mono-crystalline, back contacted) and HiT (heterojunction with intrinsic thin-layer). The PV modules were installed at Saida city which is located at the fringe of high plateaux nearby Algeria's Sahara. Saida city is recognised by its semi-arid climate due to its proximity to Sahara. The PV modules were monitored for three years from January 2014 to December 2016.

After three years of exposure, the most important reduction of the effective peak power, P^*_M, was obtained for the HiT PV module, with a 6% total power reduction at the end of the monitoring period. While for the same period, the reduction of power observed in the c_Si PV module was 4.2%. Moreover, the mc_Si PV module has shown the lower power reduction trend.

The HiT and c_Si PV module technologies presented similar values of *PR*, higher than those obtained for the mc_Si PV module. For all PV modules, the *PR* shows the effect of the degradation and seasonal oscillations.

Two methods were used to analyse the R_D of each technology, the effective peak power, P^*_M, of the PV modules and the temperature corrected performance ratio, PR_{corr}.

In both methods, the HiT PV module exhibits the worst degradation rate with values of $R_D=-1.53$%/year obtained from the evolution of P^*_M, and $R_D=-1.92$%/year obtained in the analysis of PR_{corr}.

The R_D values obtained for the HiT PV module are closer to the values obtained in the south of Europe such as in Cyprus after four years of outdoor exposure.

For the mc_Si PV module, the values obtained for the degradation rate are $R_D=-0.74$%/year and $R_D=-0.83$%/year by means of the P^*_M and PR_{corr} methods respectively. These values are in the range of values reported by National Renewable Energy Laboratory (NREL).

The R_D values obtained for the c_Si PV module are $R_D=-0.58$%/year for the first method and $R_D=-0.79$%/year for the second one. These values are lower than values obtained for locations in the deep of Saharan environment in Algeria.

The HiT PV module presented a higher *FF* than the c_Si and mc_Si PV modules during the whole monitoring campaign. For all technologies, seasonal oscillations were observed. These oscillations are more relevant in the case of the mc_Si PV module and less important in the case of the HiT module.

The degradation of HiT PV modules in desert climate conditions is more important than the one observed for the rest of technologies analyzed. Moreover, this fact cannot be attributed to temperature effects. The c_Si and mc_Si PV modules have shown lower RD values, being the c_Si the best technology for desert environment.

Appendix A. Nomenclature

Variables

Isc	Short circuit current
Voc	Open circuit voltage
Δ	Temperature coefficient-power
B	Temperature coefficient- Voltage
A	Temperature coefficient-current
H	Efficiency
G	Irradiance
R_D	The degradation rate of the PV modules
P^*_M	Effective peak power
P_{DC}	DC output power of the PV module
G^*	Irradiance at STC respectively
Tf	Thermal factor
T_m^*	PV module temperature at STC
V_m	Voltage at the maximum power point
I_m	Current at the maximum power point
FF	Fill factor
PR	The performance ratio of the PV modules
Y	Array yield
E	DC energy output
Y_r	Reference yield
τ	Recording interval
PR_{corr}	Corrected performance ratio
E_{corr}	Corrected DC energy output
L_T	The temperature losses

Abbreviations

mc-Si	Multi-crystalline
c_Si	Mono-crystalline
HiT	Heterojunction with intrinsic thin-layer
PV	Photovoltaic
AM1.5G	The global standard spectrum
STC	Standard test conditions
MPP	Maximum power point

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